

Uncertainties in The Interstellar Extinction Curve and the Cepheid Distance to M101

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ABSTRACT

I revisit the Cepheid-distance determination to the nearby spiral galaxy M101 (Pinwheel Galaxy) of Shappee & Stanek (2011), in light of several recent investigations questioning the shape of the interstellar extinction curve at $\lambda \approx 8,000 \text{ \AA}$ (*i.e.* I-band). I find that the relatively steep extinction ratio $A_I/E(V-I) = 1.1450$ (Fitzpatrick & Massa 2007) is slightly favoured relative to $A_I/E(V-I) = 1.2899$ (Fitzpatrick 1999) and significantly favoured relative the historically canonical value of $A_I/E(V-I) = 1.4695$ (Cardelli et al. 1989). The steeper extinction curves, with lower values of $A_I/E(V-I)$, yield fits with reduced scatter, metallicity-dependences to the dereddened Cepheid luminosities that are closer to values inferred in the local group, and that are less sensitive to the choice of reddening cut imposed in the sample selection. The increase in distance modulus to M101 when using the preferred extinction curve is $\Delta\mu \sim 0.06 \text{ mag}$, resulting in an estimate of the distance modulus to M101 relative to the LMC of $\Delta\mu_{\text{LMC}} \approx 10.72 \pm 0.03 \text{ (stat)}$. The best-fit metallicity-dependence is $dM_I/d[\text{O}/\text{H}] \approx (-0.38 \pm 0.14 \text{ (stat)}) \text{ mag dex}^{-1}$.

Key words: distance scale – stars: variables: Cepheids – ISM: dust, extinction – galaxies: individual: (M101)

1 INTRODUCTION

Interstellar extinction causes luminosity sources to appear fainter and redder, and is thus somewhat degenerate with distance which causes luminosity sources to appear fainter but not redder. In principle, this difference (the colour offset) can allow one to break the degeneracy between interstellar extinction and distance. If one assumes a consistent total-to-selective extinction ratio $R_I = A_I/E(V-I) = A_I/(A_V - A_I)$, one can estimate a “Wesenheit¹ magnitude” (Madore 1982) that is nominally reddening-independent:

$$W_I = I - R_I \times (V - I). \quad (1)$$

The values of R_I regularly used in the literature range from 1.60 (Paczynski et al. 1994), 1.55 (Majaess et al. 2011; Ngeow 2012), down to 1.45 (Macri et al. 2006; Gerke et al. 2011; Shappee & Stanek 2011). There is certainly a strong empirical basis for this assumption. Cardelli et al. (1989), in their seminal investigation of extinction from the ultraviolet to the near-infrared, yielded parametric fits for the extinction curve as a function of wavelength and the free-parameter $R_V = A_V/E(B-V)$. For the case $R_V = 3.1$,

their functions yield $R_I \approx 1.45$. The results of Cardelli et al. (1989) are a linchpin of astronomy as a whole, with over 5,000 refereed citations at the time of writing. These values have had convincing independent support elsewhere. Udalski (2003) measured $R_I = 1.44 \pm 0.03$ toward the Large Magellanic Cloud (LMC), which is the anchor of the extragalactic distance scale (Freedman et al. 2001) and many investigations of Cepheids. Pejcha & Kochanek (2012) developed a comprehensive physical model and matched to $\sim 177,000$ photometric measurements from a sample of 287 LMC, Small Magellanic Cloud (SMC), and Milky Way Cepheids. They measured a best-fit mean extinction curve of $R_V \approx 3.127$, assuming the formalism from Cardelli et al. (1989). Similarly, Pejcha & Prieto (2014), matched to $\sim 6,800$ photometric measurements over a broad range of wavelengths, and showed that the $R_V = 3.1$ extinction curve from Cardelli et al. (1989) is an effective fit to the *UBVRI* light curves of Type-II plateau supernovae.

There has been recent evidence that the extinction curve of even the diffuse interstellar medium may be variable on a systematic basis, or simply distinct than as parameterised by Cardelli et al. (1989). Schlafly & Finkbeiner (2011) studied reddening values toward Milky Way halo stars, and found that the extinction curve of Fitzpatrick (1999), with its different method of derivation with the ex-

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¹ “Wesenheit” is the German word for “essential”.

tion curve fit to some cubic spline anchor points rather than seventh degree polynomials among other distinctions, and its steeper extinction in the wavelength range $6,000 \text{ \AA} \leq \lambda \leq 9,000 \text{ \AA}$, was more consistent with observations that of Cardelli et al. (1989). This finding contributed to a revision of the SFD extinction maps (Schlegel et al. 1998). Similarly, Sung & Bessell (2014) showed that reddening toward open clusters within 3 Kpc of the Sun is well-fit by an $R_V = 3.1$ Fitzpatrick (1999) extinction curve, which predicts $R_I \approx 1.27$ for hot stars. Further, it is by now well-documented that the inner-parts of the Milky Way, which are rigorously investigated, are fit by a steeper standard extinction curve than the $R_V = 3.1$ curve from Cardelli et al. (1989). In their study of 17,000 Galactic bulge RR Lyrae stars identified in OGLE-III photometry (Szymański et al. 2011), Pietrukowicz et al. (2012) measure $R_I = 1.080 \pm 0.007$. Nataf et al. (2013) used red clump stars (which are $\sim 2,000$ Kelvin colder and $\sim 10\times$ more metal-rich) measured with the same OGLE-III photometry and obtained $\langle R_I \rangle = 1.218$, with significant variations confirmed spanning a range $1.0 \lesssim R_I \lesssim 1.4$. The large shifts in the extinction curve are observed to take place toward sightlines closer to one another than 0.5 degrees on the sky, or a transverse distance no greater than 75 parsecs. Finally, from the extinction study of Berdnikov et al. (1996), which based purely off photometry of Cepheids², $R_I \approx 1.07$.

Reading this sequence of findings some may argue that the astronomical community should simply switch to using the Fitzpatrick (1999) extinction curve as default over that of Cardelli et al. (1989). That may turn out to be the correct course of action, but as of now there at least three causes for concern with this approach. First, as discussed earlier in the introduction, the extinction curve of Cardelli et al. (1989) does have convincing independent empirical support, and this would need to be explained if the $R_V = 3.1$ extinction curve of Cardelli et al. (1989) turns out to be incorrect. Second, the evidence is currently overwhelming that the extinction curve of Fitzpatrick (1999) fails in the near-IR, where Fitzpatrick (1999) predicts $A_J/A_K \approx 2.31$ that is nearly independent of R_V . However, the most precisely and accurately measured value in the Galactic astronomy literature is $A_J/A_K \approx 3.02$ (Nishiyama et al. 2009). Finally, buoyed by more abundant data and a different mode of analysis, Fitzpatrick himself argued for a different mean Galactic extinction curve in Fitzpatrick & Massa (2007) (see their Table 5), which is as distinct from Fitzpatrick (1999) as Fitzpatrick (1999) is from Cardelli et al. (1989).

Separately and independently to these issues, evidence has recently emerged that the wavelength-dependence of interstellar extinction is a function of the spectral type and the specific-star-formation rate of a galaxy (Kriek & Conroy 2013), and even location within a galaxy (Zasowski et al. 2009; Phillips et al. 2013; Dong et al. 2014). During the referee process for this paper, Fausnaugh et al. (2014) found a best-fit extinction curve toward the Cepheids of NGC 4258

of $R_V = 4.9$, which is extremely shallow, using a combination of *UBVR* photometry.

Having worked extensively on some of these issues, I cannot argue at this time that there is a convincing framework unifying these disparate, seemingly mutually-inconsistent findings. What I am confident in, is that more investigation is needed, both of the shape of the extinction curve, how it varies with direction, and how this hitherto largely ignored source of systematic error has metastasised into the general astronomy literature and its library of accepted values. There is an abundance of data available in a broad range of bandpasses for a broad range of objects observed in a broad range of contexts, and thus further research that could elucidate these issues is possible.

Thus, I tackle the Cepheid distance to M101 for two reasons. First, as a probe of the interstellar extinction curve in and of itself. The data products of Shappee & Stanek (2011) are of high quality, with the photometry obtained from the *Hubble Space Telescope* (HST) and reduced via a suite of state-of-the-art software tools. The observations are of a spiral galaxy of similar mass and morphology as the Milky Way. As M101 is viewed nearly face-on, the reddening values are sufficiently small that a large number of Cepheids can be identified. Indeed, the catalogue of Shappee & Stanek (2011) is one of the largest homogeneously-measured extragalactic catalogues of Cepheids, containing 1,227 Cepheid candidates. Second, this investigation can help discern what impact these uncertainties might have on the field of the extragalactic distance ladder, where Cepheids are a widely-used standardisable candle (Macri et al. 2006; Riess et al. 2011; Gerke et al. 2011; Efsthathiou 2014). As the era of precision cosmology is now over a decade old (Spergel et al. 2003), with the reported error bars growing smaller and potential tensions growing greater (Planck Collaboration et al. 2013), the requirements for measurement precision are now higher-than-ever, necessitating diligent investigations of parameters such as extinction coefficients.

2 DEFINING THE PROBLEM AND METHODOLOGY

As discussed in the introduction, virtually any extinction coefficient in the range $1.05 \lesssim R_I \lesssim 1.45$ can be assigned some empirical support ascribing it the designation of “the standard extinction ratio for the diffuse interstellar medium.” That is problematic and a source of major systematic error previously undiagnosed and unquantified in the literature on the use of Cepheids to probe the extragalactic distance ladder. In this paper, I test for three different cases. These are the extinction curves of Cardelli et al. (1989), Fitzpatrick (1999), and Fitzpatrick & Massa (2007), which are shown in Figure 1. I convolve these curves with the transmission functions of the Landolt (1992) *V* and *I* filters (also shown in Figure 1), and a synthetic spectrum of a $T_{\text{eff}} = 5,750$ Kelvin, $[\text{Fe}/\text{H}] = 0$, $\log g = 1.0$ star kindly sent to me by Luca Casagrande, where the parameters are chosen to typical of Cepheids as modelled by Pejcha & Kochanek (2012). The predicted extinction coefficients are listed in Table 1.

At the request of the referee, I also list in Table 2 what the extinction coefficients would be for different assumed parameters. Shifting the temperature by 1000 Kelvin only

² From Table 4 of Berdnikov et al. (1996) one can derive $R_I = 0.84$, but that is because the *I*-band filter used in that study is centred at $\lambda \approx 8,800 \text{ \AA}$, which is at a longer wavelength than the standard Landolt filter.

Table 1. Predicted extinction coefficients for the Landolt, 2MASS, ACS, and WFC3 filter transmission curves convolved with the synthetic spectrum of a $T_{\text{eff}} = 5,750$ Kelvin, $[\text{Fe}/\text{H}] = 0$, $\log g = 1.0$ star as well as 0.40 mag of extinction at $\lambda = 5500\text{\AA}$. These are the coefficients assumed by this study.

	CCM89	F99	FM07
$A_I/E(V-I)$	1.4695	1.2899	1.1450
$A_U/A_{5500\text{\AA}}$	1.5492	1.5532	1.5276
$A_B/A_{5500\text{\AA}}$	1.2893	1.3022	1.2774
$A_V/A_{5500\text{\AA}}$	1.0020	1.0015	0.9965
$A_R/A_{5500\text{\AA}}$	0.8187	0.7854	0.7683
$A_I/A_{5500\text{\AA}}$	0.5963	0.5641	0.5319
$A_J/A_{5500\text{\AA}}$	0.2981	0.2694	0.2380
$A_H/A_{5500\text{\AA}}$	0.1825	0.1716	0.1410
$A_{Ks}/A_{5500\text{\AA}}$	0.1178	0.1160	0.0853
$A_{F555W, \text{ACS}}/A_{5500\text{\AA}}$	1.0367	1.0423	1.0356
$A_{F606W, \text{ACS}}/A_{5500\text{\AA}}$	0.9339	0.9178	0.9058
$A_{F814W, \text{ACS}}/A_{5500\text{\AA}}$	0.5699	0.5406	0.5079
$A_{F555W, \text{WFC3}}/A_{5500\text{\AA}}$	1.0482	1.0521	1.0414
$A_{F606W, \text{WFC3}}/A_{5500\text{\AA}}$	0.9304	0.9138	0.9019
$A_{F814W, \text{WFC3}}/A_{5500\text{\AA}}$	0.6001	0.5671	0.5354
$A_{F110W, \text{WFC3}}/A_{5500\text{\AA}}$	0.3379	0.3184	0.2855
$A_{F125W, \text{WFC3}}/A_{5500\text{\AA}}$	0.2881	0.2686	0.2372
$A_{F160W, \text{WFC3}}/A_{5500\text{\AA}}$	0.2042	0.1907	0.1603

shifts the extinction coefficients by $\sim 1\%$ or less. The dominant uncertainty lies in the assumed extinction curve, and not the convolution of the stellar spectrum with which the transmission filters are convolved. Nevertheless, should one actually be attempting “1% cosmology”, then one should compute slightly different extinction coefficients for every Cepheid. With the two bandpasses used in this work, the shift in distance modulus is only ~ 0.003 mag, with the values of Table 1 yielding the marginally smaller distances.

I then follow the sample selection outlined in Section 4 and Section 5 of Shappee & Stanek (2011), which is based off the work of Macri et al. (2006), including the same period-luminosity relations from Udalski et al. (1999), and sample-cuts based on colour and variability amplitude ratios meant to reduce blends. However, I make a few modifications to the methodology:

(i) I use recursive 3- σ outlier rejection rather than iterative weighted-median sigma clipping to remove outliers. This consistently leads to 3 of the 231 clean Cepheids being removed from the fit, independent of the assumptions made in the fit.

(ii) The errors in the relations are computed assuming homoscedastic errors on the data points. I argue that the χ^2 estimates from the method of Macri et al. (2006) and Shappee & Stanek (2011) are problematic. The various sources of systematic error (such as the uncertain extinction curve) are in need of characterisation, and these will add to the existing errors in unexpected ways, rather than simply as a re-scaling of existing errors. Further, there is no correlation given for the errors on various variables, such as the error on the mean I -band magnitude or V -band magnitude of the Cepheids, which could be correlated. Thus it is actually impossible to compute a χ^2 from the available

Table 2. Predicted extinction coefficients for the Landolt, 2MASS, ACS, and WFC3 filter transmission curves convolved with the synthetic spectrum of a $T_{\text{eff}} = 6,750$ Kelvin, $[\text{Fe}/\text{H}] = 0$, $\log g = 1.0$ star as well as 0.40 mag of extinction at $\lambda = 5500\text{\AA}$.

	CCM89	F99	FM07
$A_I/E(V-I)$	1.4524	1.2721	1.1304
$A_U/A_{5500\text{\AA}}$	1.5395	1.5407	1.5151
$A_B/A_{5500\text{\AA}}$	1.3129	1.3233	1.2979
$A_V/A_{5500\text{\AA}}$	1.0078	1.0085	1.0035
$A_R/A_{5500\text{\AA}}$	0.8258	0.7933	0.7768
$A_I/A_{5500\text{\AA}}$	0.5969	0.5646	0.5325
$A_J/A_{5500\text{\AA}}$	0.2900	0.2702	0.2388
$A_H/A_{5500\text{\AA}}$	0.1826	0.1717	0.1411
$A_{Ks}/A_{5500\text{\AA}}$	0.1178	0.1160	0.0853
$A_{F555W, \text{ACS}}/A_{5500\text{\AA}}$	1.0435	1.0503	1.0432
$A_{F606W, \text{ACS}}/A_{5500\text{\AA}}$	0.9491	0.9360	0.9244
$A_{F814W, \text{ACS}}/A_{5500\text{\AA}}$	0.5711	0.5417	0.5090
$A_{F555W, \text{WFC3}}/A_{5500\text{\AA}}$	1.0636	1.0698	1.0583
$A_{F606W, \text{WFC3}}/A_{5500\text{\AA}}$	0.9447	0.9309	0.9195
$A_{F814W, \text{WFC3}}/A_{5500\text{\AA}}$	0.6016	0.5684	0.5368
$A_{F110W, \text{WFC3}}/A_{5500\text{\AA}}$	0.3429	0.3234	0.2904
$A_{F125W, \text{WFC3}}/A_{5500\text{\AA}}$	0.2895	0.2699	0.2385
$A_{F160W, \text{WFC3}}/A_{5500\text{\AA}}$	0.2045	0.1910	0.1606

information even if one assumes that all sources of error are known, since χ^2 is a correlation-dependent quantity.

(iii) I fit for the metallicity-dependence of the dereddened Cepheid luminosities concurrently with the fit for the relative distance modulus of M101 with respect to the LMC using a multilinear least-squares fit. In contrast, Shappee & Stanek (2011) computed the metallicity-dependence using two sequential least-squares fit, with the distance modulus computed first independently of the metallicity-dependence, and the scatter to the first relation then regressed with respect to the metallicity.

(iv) Shappee & Stanek (2011) set their metallicity zero-point to $[\text{O}/\text{H}] = 8.50$, which is thus their assumed metallicity for the LMC. I instead use $[\text{O}/\text{H}] = 8.36$, as argued by Bresolin (2011), which was assumed by Riess et al. (2011) and is consistent with the measurement of $[\text{O}/\text{H}] = 8.37$ in HII regions and supernovae remnants of the LMC (Russell & Dopita 1990).

(v) As this investigation is concerned with quantifying one particular systematic error, the estimates of various parameters state only the maximum-likelihood values and the statistical errors. In contrast to Shappee & Stanek (2011) who report estimates of the total systematic error separate from their statistical errors.

3 RESULTS

3.1 Metallicity-Dependence as a Free Parameter

Assuming the extinction curve of Cardelli et al. (1989), I obtain:

$$\Delta\mu_{\text{LMC}} = (10.663 \pm 0.031) + (-0.433 \pm 0.145)([\text{O}/\text{H}] - 8.36) \\ \delta = 0.1680, \quad (2)$$

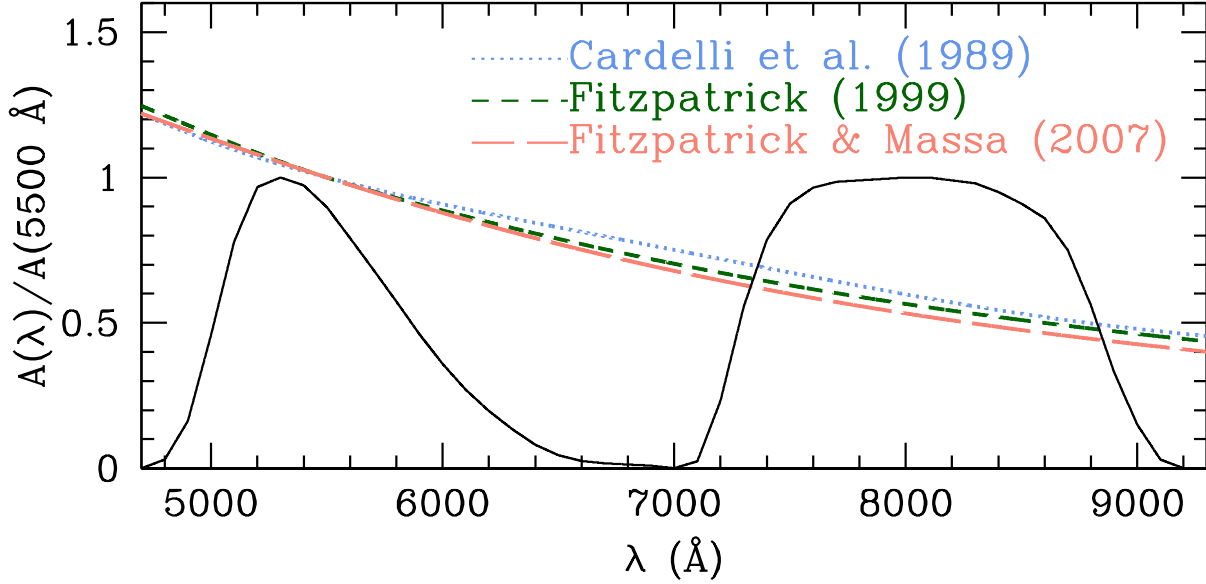


Figure 1. The extinction curves of Cardelli et al. (1989) as the dotted-blue line, Fitzpatrick (1999) as the short-dashed-green, and Fitzpatrick & Massa (2007) as the long-dashed-salmon line, as a function of wavelength. Also shown are the Landolt (1992) *V* and Landolt *I* filters in black. The different trends of the extinction curves over this wavelength regime lead to different predictions for the extinction ratio $A_I/E(V - I)$.

where δ is the $1-\sigma$ scatter on the relation. If I assume the extinction curve of Fitzpatrick (1999):

$$\begin{aligned} \Delta\mu_{\text{LMC}} &= (10.692 \pm 0.031) + (-0.406 \pm 0.144)([\text{O}/\text{H}] - 8.36) \\ \delta &= 0.1671, \end{aligned} \quad (3)$$

and for the extinction curve of Fitzpatrick & Massa (2007):

$$\begin{aligned} \Delta\mu_{\text{LMC}} &= (10.716 \pm 0.031) + (-0.384 \pm 0.144)([\text{O}/\text{H}] - 8.36) \\ \delta &= 0.1674, \end{aligned} \quad (4)$$

I reiterate that the errors quoted are random errors resulting from the assumption of homoscedastic errors on the data points. A complete inventory of the systematics involved in Cepheid determinations and their associated correlations is not available at this time and is beyond the scope of this work. Only one systematic is being focused on: the shape of the extinction curve.

The relative distance estimate from Equations 2,3,4 is ~ 0.03 mag greater than that from Shappee & Stanek (2011) in spite of assuming the same extinction curve and nearly the same selection function. The offset is largely due to the downward adjustment of the assumed LMC metallicity by ~ 0.14 dex.

For the distance relations fit by Equation 2 through to Equation 6 in the following subsection, the same three outliers and no others are always removed: F2-3598, F1-3546, and F2-1458. Their respective inferred distances are ~ 0.60 mag, ~ 0.70 mag, and ~ 1.20 mag further than the relations. Due to these large offsets and the fact that it's the same three outliers removed each time, I argue that the recursive $3-\sigma$ outlier rejection does not detrimentally bias the results.

The metallicity dependence derived, $\gamma = dM_I/d[M/H] \approx 0.40$ mag dex $^{-1}$, is substantially lower than the values of 0.72 mag dex $^{-1}$ and 0.80 mag dex $^{-1}$

that Shappee & Stanek (2011) derive using two different methods. That may be due to the different method of fitting. The value derived here is closer to other literature estimates derived from other estimates, as will be shown in the subsequent subsection.

3.2 Metallicity-Dependence Fixed to Literature Values

It is of interest to verify how results differ when the metallicity-dependence is fixed to literature values. Sakai et al. (2004) estimated $\gamma = -0.24 \pm 0.05$ mag dex $^{-1}$ by comparing tip of the red giant branch magnitudes to Cepheid magnitudes for 7 nearby galaxies images in *V* and *I* with HST, as well as 10 additional values found in the literature. Storm et al. (2011) estimated $\gamma = -0.23 \pm 0.10$ mag dex $^{-1}$ for a sample of 51 Cepheids from the SMC, the LMC, and the Milky Way. I adopt the value of $\gamma = -0.23$ mag dex $^{-1}$ though the two values are so similar that the effect of this choice is negligible.

The relation obtained for the extinction curve of Cardelli et al. (1989) is:

$$\begin{aligned} \Delta\mu_{\text{LMC}} &= (10.622 \pm 0.011) \\ \delta &= 0.1687, \end{aligned} \quad (5)$$

for the extinction curve of Fitzpatrick (1999):

$$\begin{aligned} \Delta\mu_{\text{LMC}} &= (10.657 \pm 0.011) \\ \delta &= 0.1676, \end{aligned} \quad (6)$$

and for the extinction curve of Fitzpatrick & Massa (2007):

$$\begin{aligned} \Delta\mu_{\text{LMC}} &= (10.685 \pm 0.011) \\ \delta &= 0.1678, \end{aligned} \quad (7)$$

M101 is shifted to a distance that is ~ 0.04 mag further

Table 3. The slope of the shift in inferred distance modulus per 1 magnitude increase in the reddening cut, as a function of assumed extinction curve. The curve of Fitzpatrick & Massa (2007) yields the smallest dependence to the choice of colour cut.

CCM89	-0.063
F99	-0.027
FM07	-0.017

away in all three cases relative to the values obtained when the metallicity-dependence is floated as a free parameter. That offset comes from the product of the mean $[O/H]$ of M101 relative to the LMC (~ 0.20 dex) and the shift in the slope of the metallicity-dependence (~ 0.15 - 0.20 mag dex $^{-1}$).

Though this was interesting as an exercise, I note that this assumption of a metallicity-dependence from the literature is inconsistent with other assumptions in this investigation. Storm et al. (2011) assumed a universal, constant extinction function of $R_V = 3.23$ from Cardelli et al. (1989), corresponding to $A_I/E(V-I) \approx 1.50$. That’s marginally shallower than the LMC value of $A_I/E(V-I) = 1.44 \pm 0.03$ (Udalski 2003), and substantially shallower than the Milky Way value of $A_I/E(V-I) \approx 1.27$ suggested by the work of Schlafly & Finkbeiner (2011). It may also be distinct from the SMC value. There is an urgent need for an investigation of the metallicity-dependence of Cepheid luminosities that accounts for extinction curve uncertainties and variations in the Milky Way Galaxy and its satellites.

3.3 Shifting the Maximum-Colour Cut

Shappee & Stanek (2011) removed Cepheids with $E(V-I) > 0.39$ from their fit, on the basis that they might either be red blends, or have high-reddening values that would lead to an error linearly proportional to the error in the assumed extinction curve. Of interest would be to test which of the three extinction curves yields a distance least sensitive to the choice of $E(V-I)$ cut (hereafter: $E(V-I)_{\text{Max}}$). For this calculation, I fix the metallicity-dependence to the literature value of $\gamma = -0.23$ mag dex $^{-1}$ (Storm et al. 2011) to restrict the number of degrees of freedom, though it is noted that the results are nearly identical if I fix the metallicity dependence to the values found in Equations 2, 3, and 4.

With this test, of which I plot the results in Figure 2, the extinction curve of Fitzpatrick & Massa (2007) is the most successful at matching the data for M101, whereas that of Cardelli et al. (1989) which is the most standard in the Cepheid literature is the least successful. The inferred relative distance modulus decreases rapidly as more reddened sources are included when I assume the extinction curve of Cardelli et al. (1989), exactly what one would expect if the extinction curve is too shallow. The distance modulus also decreases when I assume the extinction curves of Fitzpatrick (1999) Fitzpatrick & Massa (2007), but by a much smaller amount, ~ -0.027 and ~ -0.017 respective decreases in distance modulus per 1 magnitude increase in $E(V-I)_{\text{Max}}$. In contrast, use of the extinction curve of Cardelli et al. (1989) yields a much steeper sensitivity of ~ -0.063 . These results are listed in Table 3.

The same conclusions are reached if one would rather

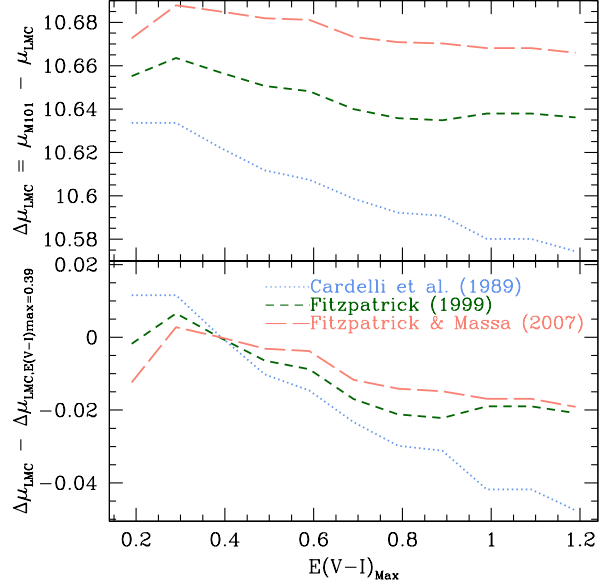


Figure 2. TOP: The distance modulus of M101 relative to that of the LMC as a function of the extinction curves and as the maximum reddening $E(V-I)_{\text{Max}}$ of Cepheids included in the calculation. The extinction curve of Fitzpatrick & Massa (2007) is the least sensitive to the choice of $E(V-I)_{\text{Max}}$, whereas that of Cardelli et al. (1989) is the most sensitive. BOTTOM: Same as top panel, but with the distance modulus for $E(V-I)_{\text{Max}} = 0.39$ (the value assumed by Shappee & Stanek 2011), shifted to zero.

Table 4. Scatter in distance modulus as a function of colour-cut on the Cepheid sample and the choice of the extinction curve. The extinction curve of Fitzpatrick & Massa (2007) yields the smallest increase in scatter as the colour cut is increased.

$E(V-I)_{\text{Max}}$	CCM89	F99	FM07
0.39	0.1687	0.1676	0.1678
0.99	0.1844	0.1839	0.1766

track the scatter in the relations rather than the shift in distance modulus, for which the results are listed in Table 4. Assuming the extinction curve of Cardelli et al. (1989), I find that the scatter increases from $\sigma = 0.1687$ at $E(V-I)_{\text{Max}} = 0.39$ to $\sigma = 0.1844$ at $E(V-I)_{\text{Max}} = 0.99$. With the extinction curve of Fitzpatrick (1999), the scatter increases from $\sigma = 0.1676$ to $\sigma = 0.1839$. Finally, with the extinction curve of Fitzpatrick & Massa (2007), the scatter increases from $\sigma = 0.1678$ to $\sigma = 0.1766$. The increase in variance for the shallowest extinction curve as the reddening cut is increased is only $\sim 10\%$, less than half what it is for the other two extinction curves.

4 DISCUSSION AND CONCLUSION

In this investigation I have demonstrated that the Cepheid-distance to the spiral galaxy M101 is measured with a reduced scatter and reduced sensitivity to systematics if I assume the mean Galactic extinction curve of

Fitzpatrick & Massa (2007), which is steeper than the canonical $R_V = 3.1$ extinction curve from Cardelli et al. (1989). The steeper extinction curve increases the distance modulus to M101 by ~ 0.06 mag. The combination of the different extinction curve, and the downward adjustment in the assumed metallicity of the LMC, yields a distance modulus estimate that is ~ 0.09 mag greater than that of Shappee & Stanek (2011), to $\Delta\mu_{\text{LMC}} \approx 10.72 \pm 0.03$. The best-fit metallicity-dependence is $dM_I/d[\text{O}/\text{H}] \approx (-0.38 \pm 0.14)$ mag dex $^{-1}$.

The mean Galactic extinction curve of Fitzpatrick & Massa (2007) yields a superior fit to the M101 Cepheids, but it should not be expected to apply in general. (Kriek & Conroy 2013) have shown that the attenuation curves of galaxies correlates with their spectral type and specific-star-formation rate. Meanwhile, it's by now well-documented that the shape of extinction curve is a function of location even in one particular galaxy (Zasowski et al. 2009; Phillips et al. 2013; Dong et al. 2014). I thus argue that a new phenomenological model to deal with interstellar extinction is needed, both to understand extragalactic stellar populations and to precisely and accurately calibrate the distance ladder.

The referee brought up the possibility of varying R_V . Given that the investigation of this work had access to data in only two bandpasses, varying R_V from a fixed family of extinction curves is indistinguishable from varying the extinction curve at fixed R_V . From the formalism of Cardelli et al. (1989), one obtains $A_I/E(V - I) = 1.145$ at $R_V \approx 2.33$, a value common in Type Ia SNe cosmology (Phillips et al. 2013). The distinction cannot be visited in this work, it could in principle be investigated if there were a larger number of bandpasses available, in particular B -band would obviously be a significant degeneracy-breaker.

Some readers may worry that the era of worrying about extinction as a source of error in the distance ladder is ending. For example, Riess et al. (2012) calibrated the near-IR period-luminosity relations for a sample of 68 Cepheids in the Andromeda galaxy (M31). This strategy is promising, as the extinction in WFC3 filter $F160W$ is only $\sim 30\%$ that of the extinction in the Landolt I -band filter, and the discrepancy in the predicted value of A_{F160W} between different extinction curves is only $\sim 5\%$ of the size of $A_{5500\text{\AA}}$ (see Table 1). However, it will also be harder to measure the Hubble flow to longer distances given the $\sim 300\%$ reduction in resolution at the longer wavelength, in addition to the possibility that Cepheids may be further blended at these longer wavelengths, for example by AGB stars which are intrinsically bright, red, and numerous. Further, regardless of this issue, the existing trove of optical Cepheid data to nearby galaxies yields a probe of the interstellar medium that is distinct from others currently in use.

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